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Renewislands—Renewable energy solutions for islands

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Abstract

Increase of the global energy demand and environmental problems relating to fossil energy utilization request the new energy sources to replace the traditional fossil fuels. With respect to energy production, most of the islands in European Union and in the other parts of the world, depend on importation, mainly from oil and its related products. The global development of renewable energy technologies can assure sustainable supply of power for islands. To overcome the limitation of the sources of renewable energy, hydrogen is utilized as a storage medium integrated with intermittent renewable energy sources such as wind and solar. This paper introduces the programme of ''Renewislands—Renewable Energy Solutions for Islands'', the work tasks, details of the design of the activities to develop solutions integrating intermittent renewable energy supply (RES), fuel cell (FC) and hydrogen infrastructure to promote RES and innovative decentralized power systems penetration in islands; main results achieved in each work packages are presented; in addition, the development of intermittent renewable energy penetration in specific European Islands are reviewed briefly.

Keywords: Islands; Intermittent; Renewable energy supply; Hydrogen; Integration system

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Contents

1. Introduction

Island development problems are mostly related to imported fossil fuel energy dependence, fresh water availability and waste management, associated with transportation and other problems. The majority of the European Islands suffer from large dependence on imported energy. The Amsterdam Treaty ratified recognizes in declaration No. 30 that "insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development." These handicaps are particularly important in energy demand and security of supply [1]. In most of the cases, there are no ways to link the islands to continental European energy production networks, making difficult the implementation of the solutions to reduce environmental costs, such as air pollution and CO_2 emissions.

Renewable energy technology is one of the solutions, which produces energy by transforming natural phenomena (or natural resources) into useful energy forms. The tremendous progresses on renewable energy indicate the feasibility to substitute fossil fuels in the near future. The advantage of renewable energy technologies are specific uses in small-scale applications such as household electricity, street lighting, irrigation systems, village water pumps or similar instruments, technologies of micro-hydro, biogas, wind generators and wind pumps operated in favourable locations [2]. Today more and more studies serve the energy supply for islands in the world [3–10].

However, the intermittency of renewable energy sources such as wind and solar poses issues related to matching electricity supply and demand and technical issues related to grid integration that result in barriers to intermittent RES penetration. The issue of intermittency and the barriers associated with it are exacerbated in small energy systems, such as islands and remote locations. Current storage technologies are not suitable to accommodate a large-scale penetration of intermittent RES. The production of hydrogen from RES may be the solution to energy storage and provide an energy vector with a variety of uses and excellent environmental characteristics. In particular, hydrogen could be used in fuel cells (FCs) for electricity, combined heat/cooling and power and transport applications with zero emissions. Hydrogen and FCs are well poised to become the prominent energy vector and conversion technology and may well shape the future energy system. However, no integrated intermittent renewable energy and H_2 storage (IRE/H_2) solution is currently available [11], considerable efforts are required for them to become a commercial reality. Research, development and demonstration on the critical technologies of hydrogen production, storage and handling and FCs is of strategic importance for Europe and could have very important socio-economic repercussions for industry and consumers.

As advertised in the EU's Campaign for take-off of the Renewable Sources of Energy, the optimization of the available potential of renewable energy technologies requires them to be used together in integrated systems [12]. These systems obviously have to be adapted to the conditions of each specific location. The aim of RenewIslands is to develop solutions and strategies for the integration of RES, hydrogen systems and FC use in islands. In addition, it would identify suitable end-users and applications, tailor solutions to fit to their requirements, assess their viability and sustainability and develop strategies for their implementation and dissemination. These would enhance RES penetration in islands and facilitate the move towards 100% renewable energy systems, thus enabling the creation of sustainable communities. Apart from increasing the penetration of intermittent renewable electricity sources, integrated RES/H_2/FC systems present advantages in that they could be integrated with the heat/cooling and transport fuel needs of islands.

This paper introduces the programme of "Renewislands—Renewable Energy Solutions for Islands", the work tasks, details of the design of the activities to develop solutions integrating intermittent renewable energy supply (RES), FC and hydrogen infrastructure to promote greater intermittent RES and innovative decentralized power systems penetration in islands and other markets, contributing to the short-term market introduction of these new technologies; main results achieved in each work packages (WPs) are presented; in addition, the development of intermittent renewable energy penetration in specific European Islands are reviewed briefly.

2. Review of intermittent renewable energy penetration in specific European Islands

After experiencing different developments renewable energies penetration in the European Islands relies on their renewable resources and the politics undertaken. Renewable energies are most developed in some islands which are trying to achieve 100% power consumption supported by renewable energies. Renewable energy penetration in specific European Islands was reviewed in the project for understanding their present

status and the feasibilities of enhancing its penetration through applying integrated RES/H_2/FC systems in islands and remote areas.

2.1. Canary Islands (Spain)

Political and environmental concerns result in a particular energetic strategy in the Canaries, which shows the importance of improving the indigenous energetic resources, the renewable energies, towards the goal for energy supply with stable offer, low cost and environmental friendliness [13,14].

In the Canaries, wind energy has been developed well with annual increase (Table 1) [13–16]. In recent years solar energy has been enhanced, and the amounts of installed solar thermal panels and photovoltaic systems expanded. Previous studies [13,14,17] indicated that in an isolated system, energy storage is important for the use of the great wind potential of the islands.

2.2. Renewable energies penetration in Ærø Island (Denmark)

The solar energy is used for district heating, being the major energy source in Ærø Island. Currently the amount of thermal solar panels installed, 3.7 m^2 per inhabitant (total

Table 1
Wind energy production per island in the Canaries (MWh)

Year	Lanzarote	Fuerteventura	Gran Canaria	Tenerife	La Palma	La Gomera	El Hierro	Total
1990			215.98	102.00				317.98
1991			1396.34	1766.68				3163.02
1992	4204.30	970.40	4607.65	3193.05				12,975.40
1993	11,710.24	2763.30	8546.53	2857.48			312.83	26,190.38
1994	18,094.20	21,831.17	13,582.36	5241.76	2743.63		836.32	62,327.45
1995	16,882.49	24,292.31	12,757.88	5920.89	2509.74		643.53	63,006.84
1996	18,755.57	26,257.45	15,367.68	6292.89	2512.60	370.60	963.50	70,520.30
1997	12,758.35	21,362.60	28,311.67	10,504.17	2010.60	728.80	761.24	76,437.42
1998	17,443.34	25,195.20	39,792.70	23,217.23	8209.20	600.80	921.38	115,379.85
1999	17,933.85	28,037.94	110,133.73	56,691.16	9357.60	314.40	965.08	223,433.76
2000	16,107.80	25,722.93	128,588.34	62,463.67	8336.40	796.80	991.46	243,007.39

Table 2
Three district heating plants

District name	Areas of thermal solar panels (m^2)	Numbers of households heated
Marstal town	18,300	1375
Ærøskøbing	4900 (plus a wood pellet boiler of 1 MW and a straw boiler of 3.2 MW)	580
Rise	3600 (with a wood pellet boiler of 800 kW)	115

of 26,800 m^2), presents the most developed renewable energy penetration for a certain area [18]. There are three district heating plants situated at Ærø Island (Table 2).

In the year of 2001, 20.5 GWh accounting for 57% of the total electricity consumption in Ærø was supported by 7.2 MW wind power. Ærø made the decision to work continuously to cover the islands' energy consumption 80–100% with renewable energy in the period of 10 years from 1998 to 2008 [18]. The Ærø Island was the winner of the "Danish solar city 2000" in 2000.

2.3. Renewable energies penetration in Greek Islands

Several kinds of renewable energy are utilized in the Greek Islands. Up to the last year, 50 wind parks were installed with a power of 120 MW in total, and 300 KWp of photovoltaic power systems finished installation. Also, one small hydroelectric unit (300 KW) and one biogas-burning unit (166 KW) are situated in Crete Island [19].

At the island of Ikaria, a hybrid energy system includes a typical hydroelectric unit linked with two pumping-and-storing plants of 3.8 MW, together with a wind park of 2.4 MW. In 2003, the electric system produced the power of 23 GWh in which 6.23 GWh (27.1%) was from wind, 7.96 GWh (34.6%) and 8.80 GWh (38.3%) were provided by hydroelectricity and fossil fuels, respectively.

Several papers presented their analytical data concerning the energy consumption in Greek Islands and the installed RES facilities [20–24], the results show that there are many islands with significant RES penetration; energy storage and management are required for further development of RES in the Greek Islands.

2.4. Renewable energies penetration in Madeira Islands

Hydroelectric energy is developed well in Madeira because of its mountainous orography and plenty of water. Another important renewable resource is wind potential for electricity production. The average annual increase rate of electricity generation is 7% during the period from 1991 to 2000 (Fig. 1).

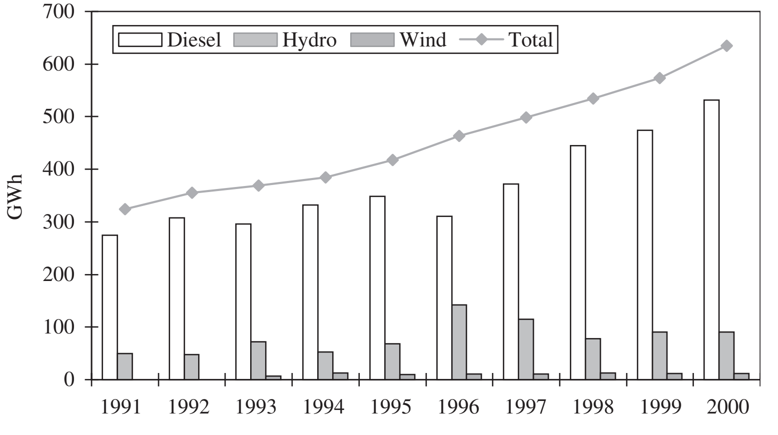


Fig. 1. Electricity production in 1991–2000.

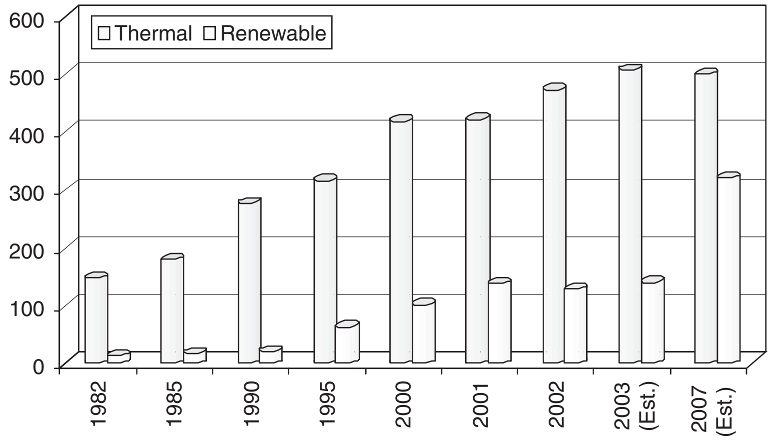


Fig. 2. Evolution of electricity production in Azores (GWh), 1982–2007.

In 2000, 16% of electricity production in the archipelago (Fig. 1) was supported by renewable energy (wind and hydro). It meant that 25 million litres of fuel oil and 15,000 l of diesel oil and the associated import costs were saved. Consequently, principal environmental pollution, CO_2 emission of 71,390 t, was cut down. The most favourable year was 1996 because renewable forms of energy provided 33% of total electricity production [25].

2.5. Energy overview of the Azores Archipelago

The Azores archipelago is composed of nine islands (Sao Miguel, Santa Maria, Terceira, Graciosa, São Jorge, Pico, Faial, Flores and Corvo) with a very rich diversity in fauna and flora. Due to the pressure of environmental protection, increasing the RES penetration is a common objective for all islands.

The total electric energy consumption in Azores was 600.8 GWh in 2002 [26], 43% of the energy produced in the archipelago was generated with clean energy sources; the rest was produced mainly in fuel oil and gasoil plants.

The study from the Forum for Energy and Development (FED) shows that there are islands that actually use modern renewable energy technologies on a large scale. For example, in 1999, 37.6% of total electricity production was contributed by renewables in São Miguel Island; hydropower is the main contributor (42.6%) in Flores Islands. Fig. 2 clearly displays main islands potential and mid-term projections [27,28].

2.6. The Cape Verde Islands

An important source of energy for Cape Verde is biomass, particularly in the rural areas. Biomass represents 37.4% of the total consumption of energy and is generally used for cooking. Three wind farms with a total capacity of 2.4 MW were installed in the main power systems of Cape Verde in 1994. The turbines are eight 300 kW Nordtank turbines. Wind energy represents the greater contribution within the renewable energies to electricity generation in the Cape Verde Islands. This is due to the good wind conditions in the

islands where the Trade Winds prevail (winds of north–east direction) and are characterized by being constant and with medium–high speeds (in some areas the speeds average is 12 m/s). In fact, wind farms in the Cape Verde Islands are the ones with bigger productivity of the world, with capacity factors (energy really produced in a year divided by the one that in theory can be produced in the same period) higher than 0.4 (40%) [29–31].

The wind power installed on the Cape Verde Islands represented 3% of total electrical power installed on the Archipelago in 2002. The penetration levels have been achieved without any wind farm dedicated control, except for the standard wind turbine controllers in each machine. Wind farm control adjustments were done manually, by the diesel power plant operators. The total technical availability has been high (92–98%). The Capeverdean government and Denmark's development agency Danida jointly financed the turbines.

Also, many researches showed the potential possibilities for renewable energy application in islands [32–40]. They analysed the technical and economic feasibility to install renewable energy systems in remote area and islands. Generally, significant progresses have been made in renewable energy technologies, and some are available commercially. However, not all renewable energy systems are mature and cost competitive, continuing efforts on research and demonstration are demanded.

3. Overview of the project renewislands

3.1. Objective of the project

The project RenewIslands aimed to contribute to the market penetration of new energy systems combining FCs, renewable energy sources and hydrogen in islands and remote regions in EU and Third Countries.

The principal objectives of the project were to: (1) analyse issues associated with intermittent RES penetration in islands and assess the potential for hydrogen energy storage; (2) understand integrated RES/H_2/FC applications and markets; (3) configure integrated RES/H_2/FC applications and develop a software tool to model their technical, economic and environmental characteristics; (4) check the technical and economic feasibility of a grid-connected integrated RES/H_2/FC installation on the example of Porto Santo, Madeira, based on an existing wind park and a desalination plant; (5) discuss opportunities for integrated RES/H_2/FC systems in islands, the effects of energy and environment regulation on their introduction, and wider dissemination issues.

3.2. International co-operation

The project involved seven partners across six European countries, consisting of universities and other research institutes, a regional energy agency, a leading electrolyser industry and island networks. The consortium presents an appropriate mix of skills (hydrogen, FC, renewable energies, dissemination and market studies) and adequate geographical distribution to accomplish the project objectives, ensure exploitation of results and their dissemination, and provide Community added-value.

Table 3
Structure of the consortium, management and resources

No.	Institution short name	*Country*	Main activity in the project	Function in the project	Involvement in WPs
1	IST	Portugal	Research, technological and feasibility studies, dissemination	Project Coordinator, WP4 Leader	WP1, WP2, WP3, WP4
2	HYDRO	Norway	Technological studies	Partner, WP2 Leader	WP1, WP2, WP3, WP4
3	E4TECH	Switzerland	Technological and feasibility studies	Partner, WP3 Leader	WP1, WP2, WP3, WP4
4	ITC	Spain	Research, technological studies, dissemination	Partner, WP1 Leader	WP1, WP2, WP3, WP4
5	AREAM	Portugal	Research, regulatory, and feasibility studies, dissemination	Partner	WP1, WP2, WP3, WP4
6	NTUA	Greece	Socio-economic studies, dissemination	Partner	WP1, WP4
7	ISLENET	Belgium	Dissemination	Partner	WP1, WP4

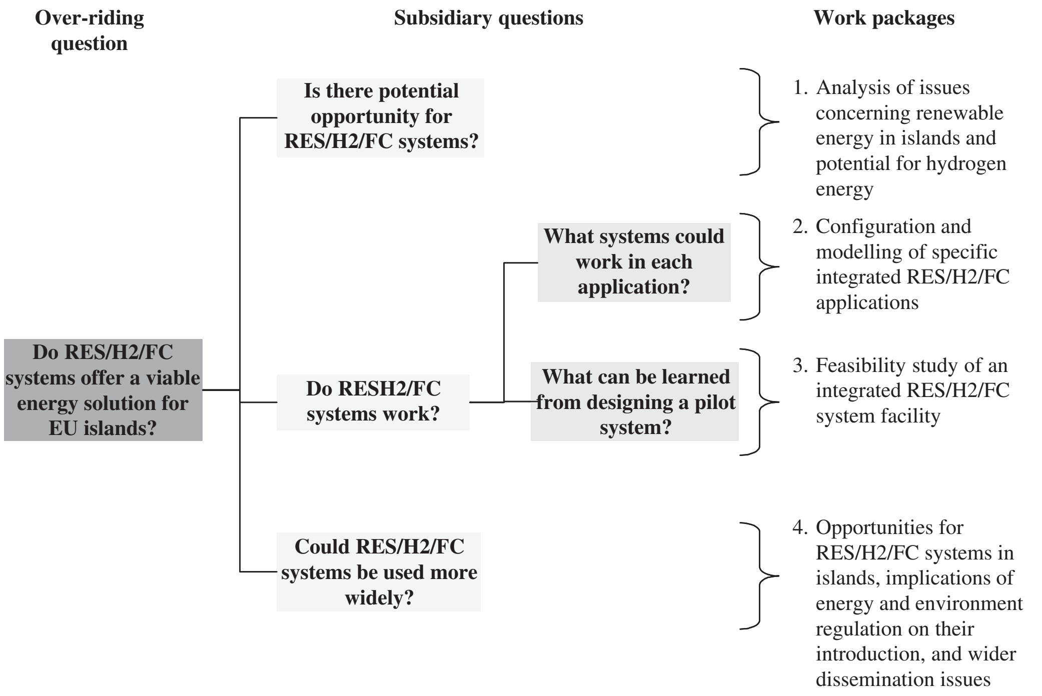


Fig. 3. Overall methodology.

3.3. Project organization and overall methodology

The project objectives were fulfilled through a total of four WPs, each with a WP leader, and consisting of a number of tasks (Table 3).

The over-riding question that this project was seeking to address whether integrated RES/H_2/FC systems can offer technically, environmentally and economically viable energy solutions that would lead to an enhanced integration of RES and decentralized power systems in EU Islands and other remote areas. In addressing this question subsidiary questions needed to be answered, which in turn created the individual WPs . The linkage of this overall methodology is shown in Fig. 3.

3.4. Activities and results achieved

The project had produced results relevant to a wide range of energy users, local authorities, energy planners, consumers' associations, industrial and private investors, tourism industries and energy companies.

3.4.1. Analysis of issues with intermittent renewable energy in islands and potential for hydrogen energy

In review of potential technical solutions to enhance renewable energy penetration in islands emphasis was placed on the analysis of solutions involving hydrogen energy storage and on the identification of end-use applications for H_2 in islands (e.g. electricity for peak

shaving, tri-generation in hotels, CHP for desalination, transport fuel). Also, this task provided an analysis of renewable energy penetration and the role for hydrogen energy storage in participating islands, building on the results of the above reviews and analyses. Technical issues and solutions associated with different integrated RES/H_2/FC configurations were investigated as follows:

1. *Solutions for enhanced intermittent RES penetration*: Development of energy storage technology is growing and varying rapidly. The possibility of using energy storage technology to change the traditional way of power systems is explored and planned. Energy storage has the advantages to increase asset utilization, assisting penetration of renewables, and improve the quality of electric systems in flexibility, reliability, and efficiency. General requirements of energy storage and the different electricity storage options were reviewed, hydrogen was studied as a storage medium.
2. *Hydrogen production processes and applications*: Hydrogen is an attractive energy media to be applied in islands. The processes of hydrogen production, storage and use would enhance renewable energies penetration in weak and small islands electrical grids. This work reviewed hydrogen production, water electrolysis and hydrogen distribution. Emphasis was placed on its uses both for electricity production and as fuel for transportation systems. Safety issues of hydrogen were also considered.
3. *Programme and trials of intermittent RES/H_2/FC systems*: Relevant projects on hydrogen from intermittent renewables and integrated RES/H_2/FC systems are being processed worldwide at different degrees of implementation. Some of these projects were described in this task. They are: (1) Utsira Project (Norway), (2) Hydrogen Demo Project in UK: PURE—Promoting Unst Renewable Energy, (3) Antarctic Experience: Introduction of Hydrogen Energy at Mawson, (4) Buses Running on Hydrogen for the Macaronesia (Hydrobus), (5) Integrating Self Supply into End Use for Sustainable Tourism (Green Hotel), (6) Hybrid Renewable Energy Hydrogen Production System in Gran Canaria (Canary Islands—Spain), and (7) Cluster Pilot Project for the Integration of RES into European Energy Sectors Using Hydrogen (RES2H_2).
4. *Review of intermittent renewable energy penetration in specific islands*: Renewable energies application were investigated in Canary Islands (Spain), Utsira Island (Norway), Greek Islands, Madeira Islands (Portugal), Azores Archipelago (Portugal) and Cape Verde, some general information with respect to power production and energy consumption in these Archipelagos were introduced. Special emphasis was made on analysis of energy storage requirements and hydrogen storage technologies.

3.4.2. *Configuration and modelling of specific integrated RES/H_2/FC applications*

Three tasks were involved in the second WP. The first configured integrated RES/H_2/FC systems to be modelled, based on the integrated RES/H_2/FC opportunities and issues identified in the first WP. Configurations differed in terms of hydrogen storage location and its end-uses (e.g. peak shaving, CHP for desalination plant and surplus electricity input to the grid, tri-generation at tourist resorts, combined stationary and transport applications). The second task developed an H_2RES software model for the analysis of integrated RES/H_2/FC systems and applied the model to analysis selected system configurations. The key technical and economic characteristics of the systems were modelled under specific island energy system constraints. In the third task, it used the technical and economic modelling results to assess the viability of specific integrated

RES/H_2/FC configurations compared to alternative solutions for providing similar energy services.

Hydrogen storage in islands can be considered as a way to make use of excess renewable electricity delivered by existing or new renewable capacity. In such a context, hydrogen storage is used for solving mismatch between overall demand and supply patterns. This choice is associated with a more effective use of installed renewable technology capacity, as it makes use of otherwise wasted renewable energy sources available at times when electricity demand is low.

In an example investigated, it was shown, for example, that displacing a diesel engine peak unit could halve the total annual fuel consumption and emission rate. The choice of a very large hydrogen storage capacity (enough to act as seasonal storage) reduced significantly the number of wind turbines to be installed, leading to a better use of the installed capacity along the year [41]. The introduction of significant photovoltaic cells capacity for an unchanged storage capacity achieved similar fuel consumption and emissions rates with a much lower number of wind turbines, and a lower amount of electricity generated in excess.

A new modelling tool H_2RES developed and applied to different case studies had confirmed that using a hydrogen loop technically allowed the renewable penetration rate to reach 100%. However, because of the high costs of hydrogen-related technologies and lack of experience with their integration in grid applications, a possible first step was to consider peak shaving schemes with FCs fuelled with renewable hydrogen. Such an option had been investigated for the islands of Porto Santo and Sal, and it was shown that with such schemes, the renewable penetration could reach, respectively, 16% and 18% in these two islands [42,43].

Modelling activities undertaken in this work have shown that when excess electricity cannot be exported to the grid at any time, there were environmental benefits associated with hydrogen storage due to a lower amount of fossil-based electricity imported from the grid. The annual cost of energy supply was, however, several times greater than Business as Usual even under optimistic assumptions. For stand-alone systems which aimed at 100% renewable energy, hydrogen was of interest either by itself or in association with batteries, as it had the potential to be more economic than batteries by themselves over the system lifetime.

On the other hand, when excess electricity could be exported to the grid at any time, there was no rationale for the introduction of hydrogen storage within grid-connected distributed energy systems if the electricity selling and buying prices were uniform throughout the day. It was much more costly than configurations without storage, while at the same time less environmental, as direct use of renewable sources was much more energy efficient and displaced fossil-based electricity into the grid.

Islands and remote regions have more similarities than differences, from energy point of view, so the same methodology may be applied to both.

3.4.3. Feasibility study an integrated RES/H_2/FC system pilot facility

Four tasks were studied in this WP. Firstly, the project analysed electricity demand and wind electricity supply in the island of Porto Santo, and described a wind/H2/diesel system to serve the island. Information about energy consumption and wind energy production of Porto Santo were obtained in previous WPs. Technical preparations of a hydrogen energy system for the entire island were also considered.

Secondly, the basic design of the hydrogen energy system to be used in Porto Santo was given. The facility consisted of, based on preliminary system considerations and components availability, a 75 kW (hydrogen output) electrolyser, a 300 kWh hydrogen storage (max.), a 25 kW FC and system control and monitoring equipment. The facility would be integrated with an existing 1.1 MW wind farm in Porto Santo and would use its surplus electricity to produce hydrogen. System performance was modelled using the model developed in WP2.

Furthermore, modelling of facility key operating and performance parameters was analysed. These parameters are important in assessing the techno-economic viability and environmental benefits of the scheme and similar systems.

The fourth task focused on planning, safety and regulatory issues and how to address them. It also discussed issues related to performance monitoring and analysis of the pilot facility, useful for validating modelling data and for assessing the viability of the scheme and future systems.

For the possibilities to introduce Wind/Hydrogen energy systems into the existing diesel engine in Porto Santo grid, the following results drawn from the research activities for this WP were obtained: (1) large wind energy application would increase costs invested; (2) economic analysis showed that wind energy utilization is limited in islands, which reaches about 50% of peak load; (3) the processes for applying hydrogen energy system in the island of Porto Santo should be gradual, in several phases; (4) deploying renewable energy projects, it is important to have careful planning; early communications with authorities and the public would smoothen project implementation.

3.4.4. *Opportunities for integrated RES/H_2/FC systems in islands, the effects of energy and environment regulation on their introduction, and wider dissemination issues*

Two tasks were undertaken in the following actions. The programme reviewed relevant EU, national and regional energy and environment legislation and discussion of issues regarding norms and standards related to integrated RES/H_2 systems and H_2 end-use. This task provided a review of relevant EU, national and regional energy and environment legislation that influences the uptake of RES and that affects the development of integrated RES/H_2/FC systems. Table 4 lists EU legislation pertaining to renewable energy sources in

Table 4
Legal instruments since 2000

The Directive on the promotion of electricity produced from renewable energy sources, 2001/77/EC-OJ L283/33—27.10.2001	The Directives on labelling of electric ovens, of airconditioners and of refrigerators 2002/40/EC-OJ L283/45—15.5.2002 2002/31/EC-OJ L86/26—3.4.2003 2003/66/EC-OJ L170/10—9.7.2003
The Directive on energy performance of buildings, 2002/91/EC-OJ L1/65—4.1.2003	
The Directive on the promotion of biofuels 2003/30/EC-OJ L123/42—17.5.2003	The Regulation on Energy Star labelling for office equipment, 2001/2422/EC-OJ L332/1—15.12.2001
The Directive for the taxation of energy products and electricity, 2003/96/EC-OJ L283/51—31.10.2003	The Directive on Eco design requirements for energy using products, Proposal COM (2003) 453
The Directive on the promotion of cogeneration, 2004/8/EC-OJ L52/50—21.2.2004	The Directive on energy efficiency and energy services, Proposal COM (2003) 739

recent years. It discussed issues related to norms and standards with regard to integrated RES/H_2 systems and H_2 end-use.

Another task discussed drivers and barriers to greater RES penetration and development of integrated $RES/H_2/FC$ systems. This task built on the review of task 1 and identified drivers and barriers to a greater RES penetration and development of integrated $RES/H_2/FC$ systems across the EU and for islands in particular.

Norms and standards concerning the hydrogen application in the energy sector have been addressed in several EU and other international projects and networks [44–47]. Codes and standards for the use of hydrogen as an energy carrier have been studied. Currently other norms and standards are being referred for the early implementation of hydrogen energy systems.

Without dedicated standards it is a challenge to obtain the approval from the authorities for hydrogen system installations. However, early standards that are ahead of mature hydrogen technology might hinder current technology choices and innovation.

The relevant RES legislation advocates increasing the renewable energy penetration for energy safety supply and environment protection, this could be as a main drive to a greater RES penetration and development of integrated $RES/H_2/FC$ systems across the EU and for islands in particular. Special European laws and financial supports are required to meet the demands of energy autonomy of islands without environment impacts.

4. Conclusions

Today, deployment of renewable energy in islands is a great opportunity to test new technologies, in circumstances where conventional technologies are costly, and new solutions are more efficient.

The project contributed to devising the ways to increase the market penetration of new energy systems combining FCs, renewable energy sources and hydrogen in islands and remote regions in EU and Third Countries. It has developed solutions integrating intermittent RES, FC and hydrogen infrastructure to promote greater intermittent RES and innovative decentralized power systems penetration in islands and other markets, contributing to the market introduction of these new technologies. It has resulted in RenewIslands methodology for sustainable development of islands, and has resulted in an upgrade of a dedicated island energy planning model H_2RES.

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